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SIMULATION OF LANDMINE EXPLOSION USING LS-DYNA3D SOFTWARE: Benchmark Work of Simulation of Explosion in Soil and Air

J.Wang

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Aeronautical and Maritime Research Laboratory

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ABSTRACT

This report describes the benchmark case applying LS-Dyna3d (Dyna) to simulate explosion in soil and air. Dyna simulation is compared with results from a well-defined landmine-explosion experiment. The agreement is reasonably good. This work has provided a base for further simulation of a system involving a structure, such as an army vehicle, subject to a landmine explosion.

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Executive Summary

Protection of army vehicles and personnel against landmine threats is an important issue in the area of defence research. Both experimental investigation and computational analyses play significant roles in this research. The analysis will help minimise the number of the experimental tests required, which are usually very costly, and also help to interpret the test results. Once verified by the experimental tests, it can be used as a design tool for the consequent improvement of the structural system involved. Simulation of a landmine explosion is complicated, involving an explosion causing a shock wave propagation in soil and air and then interaction with a structure. A computational tool needs to incorporate adequately these challenging factors. LS-Dyna3d (Dyna) software [1] appears to be one of the most suitable computational softwares currently available for this application. However, verification of Dyna in the area concerned has not been reported in the published literature nor provided by its developer. Since a number of assumptions and numeric approximation techniques are employed in Dyna, verification is important for each application.

This report describes the benchmark case, applying Dyna to simulate an explosion in soil and air. In the simulation an Eulerian mesh and multi-material options were used which enable the explosive products to expand into the soil and air without causing a distortion of the finite element meshes. Dyna simulation is compared with results from a well-defined landmine-explosion experiment.

Compared with experimental results the simulation for a landmine-explosion process is reasonably good. Predictions of geometry of the initial fireball expansion, formation of soil ejecta and crater, and the expansion of the cloud of explosive products agree with experiment observations reasonably well. The Dyna prediction underestimates the maximum overpressure. Compared with the average measured values, the prediction is lower by up to 50%. However the measured values are scattered. The predicted pressure is at the lower side of the range of the measured values. Dyna slightly overestimates the impulse. Similarly the measured values are scattered. The

predicted impulse is at around the upper side of the range of the measured values. The way to improve overpressure prediction is discussed in this report.

This work has provided a base for further simulation of a system involving a structure, such as an army vehicle, subject to a landmine explosion.

Authors

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John Wang received his B.E. ('82) and M.E. ('86) in mechanical engineering from Shanghai Polytechnic University. He taught Mechanical Engineering at Tongji University, Shanghai during 1982 to 1983 and 1986 to 1988, being promoted to lecturer in 1987. With the full financial support of the Australian Government John studied at the Asian Institute of Technology (AIT) from 1988 to 1991, when he received his PhD. Dr Wang then worked at AIT as a research engineer and concurrently Consultant Engineer for Thai companies. Relocating to Australia, Dr Wang was a Visiting Fellow at the University of New South Wales (UNSW) in early in 1992 before joining United Air Specialists Pty Ltd, as a mechanical engineer. From 1993 to 1999 John worked at UNSW initially as a post-doctoral fellow and later ('98) was promoted to senior research officer. Since 1999 Dr Wang has worked at Weapons Systems Division, DSTO as a research scientist. Dr Wang's research has covered several areas, including elastic-hydrodynamic lubrication, soil mechanics, mechanical vibration, rotor-bearing-foundation dynamics, advanced composite materials and structures, machine design and development, and application of finite element method. At DSTO Dr Wang has applied this experience to research on vehicle protection against landmines.

Contents

1. Introduction

Protection of army vehicles and personnel against landmine threats is an important issue in the area of defence research. Both experimental investigation and computational analyses play significant roles in this research. The analysis will help minimise the number of the experimental tests required, which are usually very costly, and also help to interpret the test results. Once verified by the experimental tests, it can be used as a design tool for the consequent improvement of the system under study.

Simulation of landmine explosion is highly complicated, involving an explosion causing a shock wave propagation in soil and air and then interaction with a structure. A computational tool needs to incorporate adequately these challenging factors. LS-Dyna3d (Dyna) software [1] appears to be a suitable code currently available for this application. In recent years it implemented the Eulerian mesh and multi-material option which has extended its modelling capacity and enabled a comprehensive solution to become feasible. However, verification of Dyna in the area concerned has not been reported in the published literature nor provided by its developer. Since a number of assumptions and numeric approximation techniques are employed in Dyna, verification is important for each application.

This report describes a benchmark case applying Dyna to simulate an explosion in soil and air. The simulation is compared with results from a well-defined landmine-explosion experiment. The agreement is reasonably good. This work has provided a base for further simulation of a system involving a structure, such as an army vehicle, subject to a landmine explosion.

2. Simulation of Landmine Explosion

For the purpose of computer code validation, Defence Research Establishment Suffield (DRES) in Canada conducted a series of explosion tests with 100g of plastic explosive C4 charges in dry sand. The full test report [2] was provided to TTCP KTA 1-34* partners. This is an excellent source of data to benchmark the simulation of explosion in soil and air using Dyna.

The test configuration used by DRES [2] is illustrated in Figure 1. The explosive charge used has a disk shape. It is buried to different depths in dry sand in a steel container. Pressure transducers were located above the soil at different heights.

In the computational simulation two cases were considered where the depths of burial (DOB) of the explosive material were 0 and 3cm, respectively. The DOB is measured

* TTCP KTA 1-34. Protection of Armoured Vehicle against Landmine is an international group made up of Australa, Canada, USA and UK

from the ground surface of soil to the top surface of the charge (Figure 1). Two transducer positions shown in Figure 1 were selected for making the comparisons between the predicted and measured pressures.

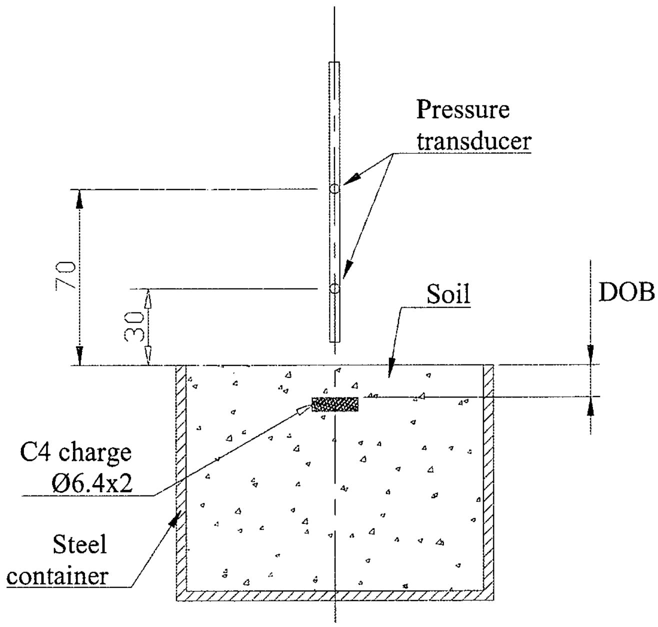


Figure 1: 100g simulated anti-personnel (AP) mine change – configuration of experiment (unit in cm)

Figures 2 and 3 respectively show the geometry and mesh of the model with DOB = 3cm. By making use of symmetry, only 1/4 of the structure is modelled. Fine mesh is generated for the explosive and for a part of the soil and air that are near the explosive. Coarse mesh is generated in the region away from the explosive. Regular rectangular brick elements are generated for the explosive, soil and part of the air above the soil. The remaining air is meshed with irregular shaped brick elements so as to reduce the total number of elements. The pressure prediction at the transducer positions is insensitive to the mesh in this area.

The exterior boundary of the air is determined in such a way that the time duration, from beginning of detonation to arrival of the shock wave at the boundary, should be sufficient for investigating pressure vs time at the positions of the transducers.

To form the symmetry condition in the finite element model (FEM), the node transitional displacement normal to the symmetry planes is constrained. The nodes along the interfaces between the air, soil and steel are merged. This is the most reliable and economic way to simulate contact. The vertical movement along the bottom of the steel container is fixed to remove the rigid-body motion of the system.

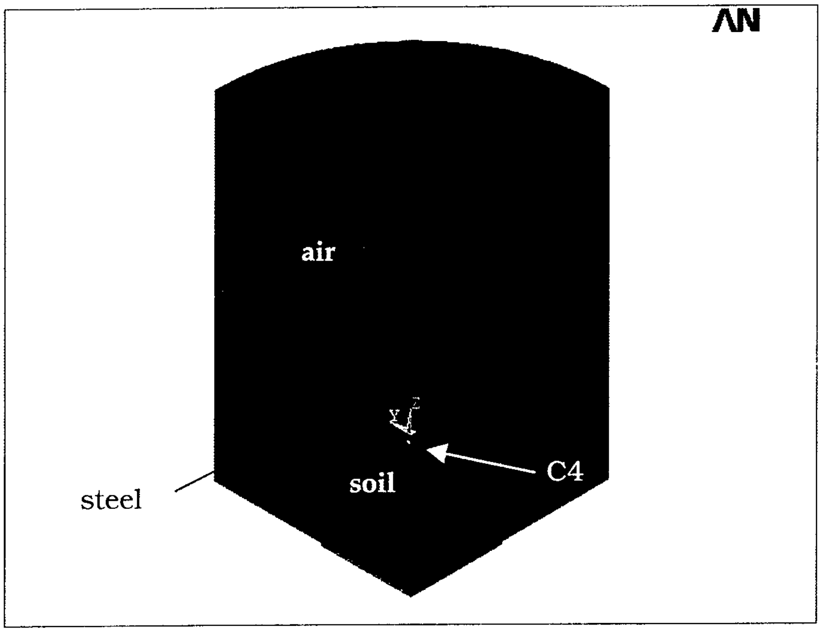
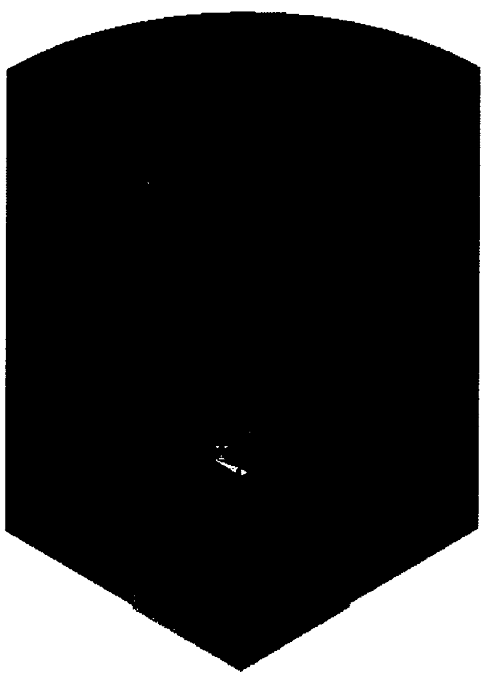
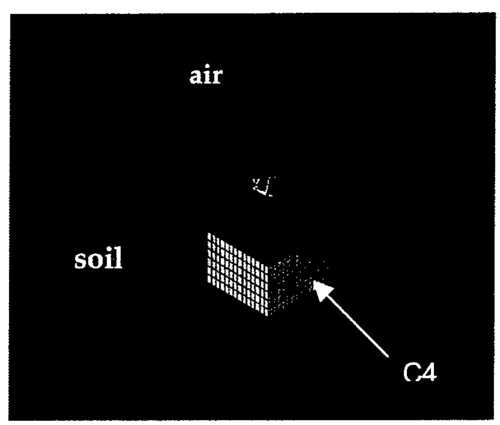


Figure 2: Geometry of the model. DOB = 3 cm



(a) Overall



(b) Local enlarged

Figure 3: Finite element mesh (DOB = 3cm)

Table 1 lists the Dyna material types used for the four materials involved. The material properties and parameters of equations of state (EOS) are also included in the table.

Table 1: Dyna Material Types, Material Property Input Data and EOS Input Data

Material	Dyna material types, material property input data and EOS input data (unit = cm, g, μs)								
C4 [3]	*MAT_HIGH_EXPLOSIVE_BURN								
	RO	D	PCJ						
	1.601	0.8193	0.28						
	*EOS_JWL								
	A	B	R1	R2	OMEG	E0	V0		
	6.0997	1.295E-1	4.50	1.40	0.250	9.00E-02	1.00		
Air	*MAT_NULL								
	RO	PC	MU						
	1.29E-3	0.0	0.0						
	*EOS_LINEAR_POLYNOMIAL								
	C0	C1	C2	C3	C4	C5	C6	E0	V0
	-1.0E-6	0.0	0.0	0.0	0.4	0.4	0.0	2.50E-6	1.0E+0
Steel	*MAT_PLASTIC_KINEMATIC								
	RO	E	PR	SIGY	ETAM	BETA			
	7.9	2.1	0.29	2.75E-3	0.021	1.00			
Soil [4]	*MAT_SOIL_AND_FOAM_FAILURE								
	RO	G	BULK	A0	A1	A2	PC	VCR	
	1.8E+0	6.385E-4	3.00E-1	3.4E-13	7.033E-7	0.30E+0	-6.90E-8	0.0	
	EPS2	EPS3	EPS4	EPS5	EPS6	EPS7	EPS8	EPS9	EPS10
	-1.04E-1	-1.61E-1	-1.92E-1	-2.24E-1	-2.46E-1	-2.71E-1	-2.83E-1	-2.9E-1	-4.0E-1
	P2	P3	P4	P5	P6	P7	P8	P9	P10
	2.0E-4	4.0E-4	6.0E-4	1.2E-3	2.0E-3	4.0E-3	6.0E-3	8.0E-3	4.1E-2

The meshes for the explosive, soil and air are modelled as Eulerian meshes and the mesh for the steel is modelled as Lagrangian mesh. The materials of the explosive, air and soil are specified as multi material.

Note that when the Eulerian mesh is used, for each time step Dyna solves the equations in two steps. In step one it treats the problem as if it was Lagrangian, ie. let the mesh follow the material flow and the mesh deforms. In step two the nodes are moved back to their initial positions (ie. the mesh is fixed) and the solution is mapped from the deformed mesh to the fixed one (advection step). Multi-material option means that up to three different materials can be modelled within the same mesh. The element properties are determined using a weight average technique, in terms of mass flux of the individual materials into the element. Thus in this application, using these techniques, the meshes are fixed in space and the explosive product is able to expand into the meshes initially occupied by the soil or air. Similarly the soil can move into the initial air mesh.

3. Results and Discussions

Dyna provides four advection methods. Advection methods 2 and 4 are commonly used. Advection method 4 is spatially first order accurate. Advection 2 is second order accurate but less stable in the computation. The advection method 2 was tried but the instability obstructed the computation. The calculation was terminated at earlier stages with an error message "negative volume in advection" even with a small scale factor used for the intergrating time step. Hence the advection method 4 was used.

A number of meshes with different mesh densities were tried. The results indicate that the mesh density significantly influences the prediction accuracy. Typically when element number increased from 31,000 to 84,000 and 129,000, the predicted overpressure increased respectively by around 16% and 18%. In addition the calculation also indicates that with a large number of elements the computation time increases drastically. For the mesh with 84,000 elements the full simulation took over 17 hours on a SGI R10000 processor workstation. Considering both the factors of computing time and accuracy, meshes with about 84,000 elements for the two cases were finally used.

3.1 Explosion Process

Figure 4 shows the soil displacement vs time after the mine is initiated, where DOB = 3cm. This figure shows soil density and thus the detonation products and air are not included in the figure. However, before the detonation products break through the soil surface (at round time = 250μs) this figure also clearly shows how the detonation products or "fire ball" expands. Figure 5 plots the expansion of explosive products vs time from time = 300μs.

These figures show that, compared with the description in the test report, Dyna reasonably simulated the mine explosion process. It describes the early expansion of the detonation products, its interaction with soil, generation of ejecta, detonation products breaking through soil surface and expanding into air, and generation of a soil crater. (Detaild comparisons are given in next section.)

Figure 6 shows a typical curve of overpressure vs time. The shock wave propagation nature is basically captured in these curves although the pressure does not rise exactly instantly at the time of arrival due to the limitations of the numeric approximation technique.

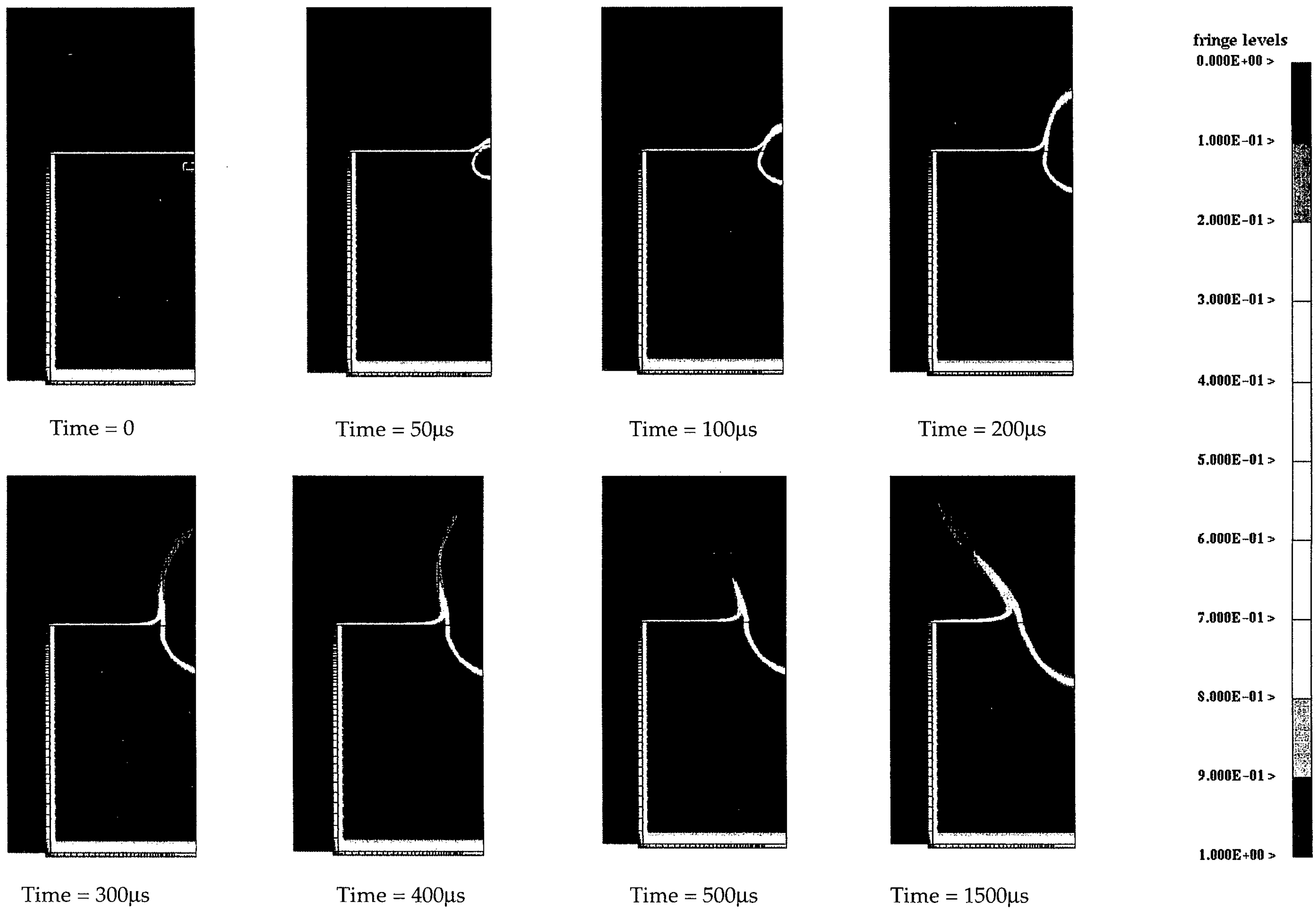


Figure 4: Soil displacement vs time, DOB = 3cm (relative soil density plot, density of undisturbed soil = 1)

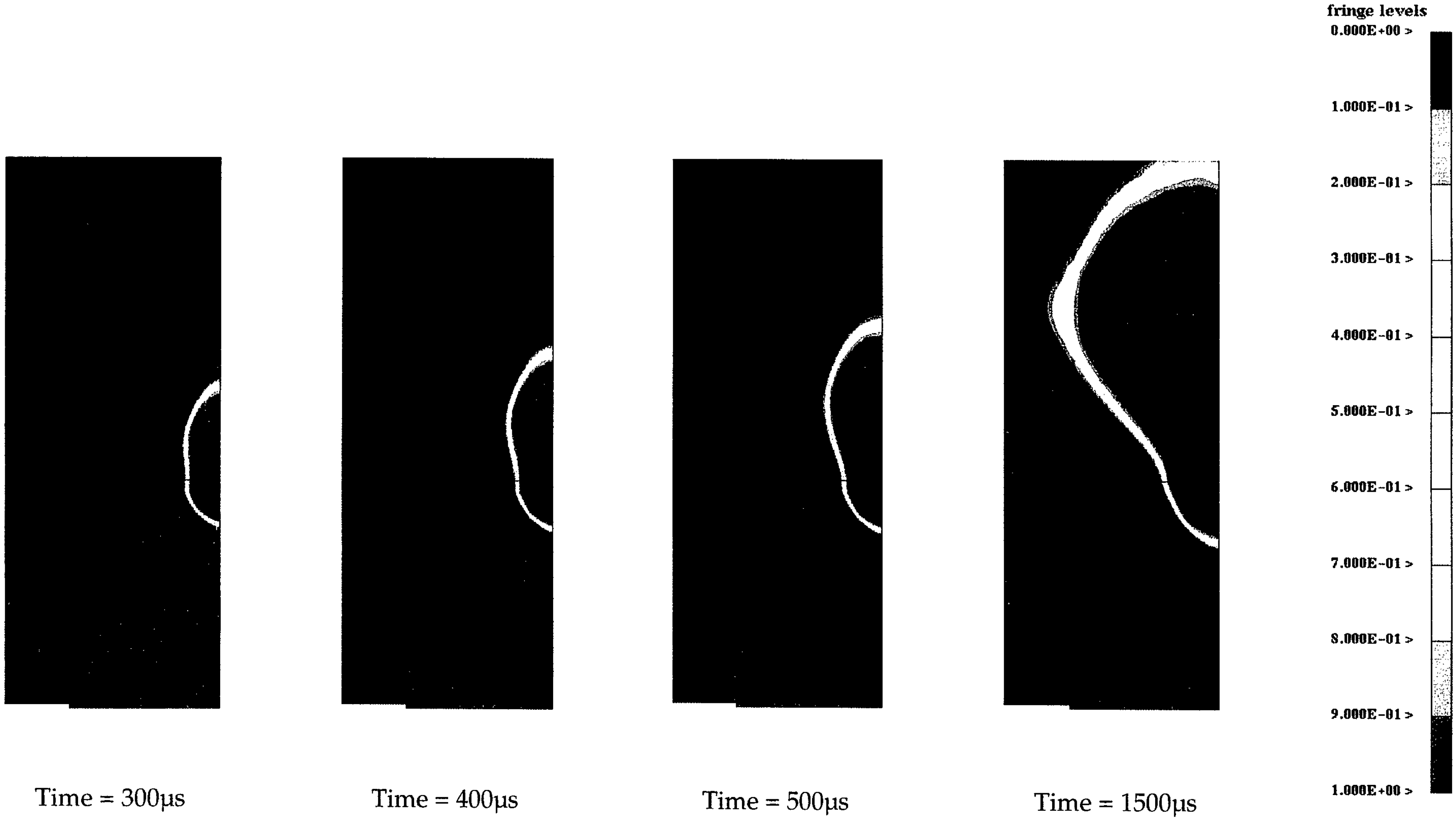


***Figure 5**: Expansion of explosive product vs time, DOB = 3cm (relative air density plot, density of undisturbed air = 1)*

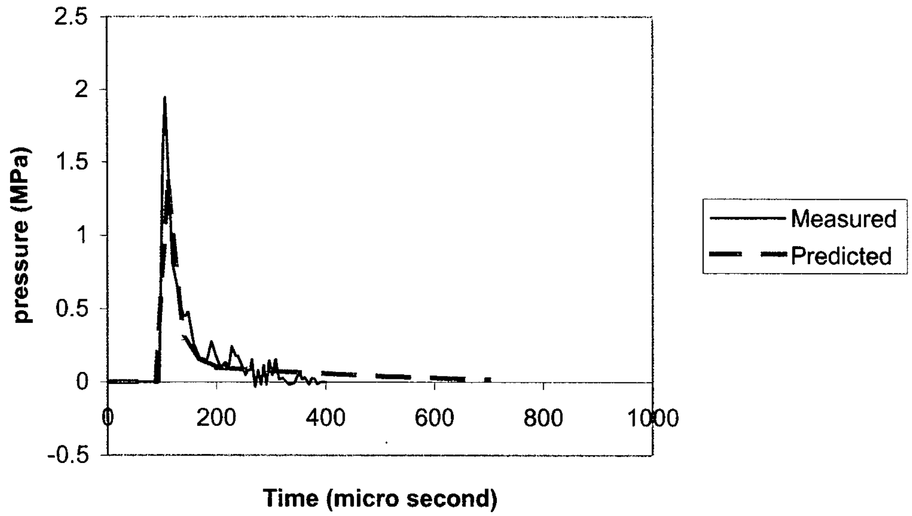


Figure 6: Overpressure vs time at transducer position 1(DOB = 0)

3.2 Comparison with Experimental Results – DOB = 3cm

The comparisons are made for the following items:

(1) Time of arrival;
(2) Peak over pressure;
(3) Positive phase impulse;
(4) Displacement of ejecta front;
(5) Width of crater;
(6) Height of the detonation products cloud; and
(7) Width of the detonation products clouds.

Figure 7 shows the comparison of the time of arrival at the two transducers' positions. The predicted results agree well with the measured results. The discrepancies between the predicted and average measured values are 2% to 10% respectively.

Figure 8 shows the comparison of the peak pressure at these positions. As shown in Figure 8 the measured values are rather scattered. The predicted values are within the range of the measured values and at the lower side of it. The discrepancies between the predicted and average measured values are 5% to 18% respectively.

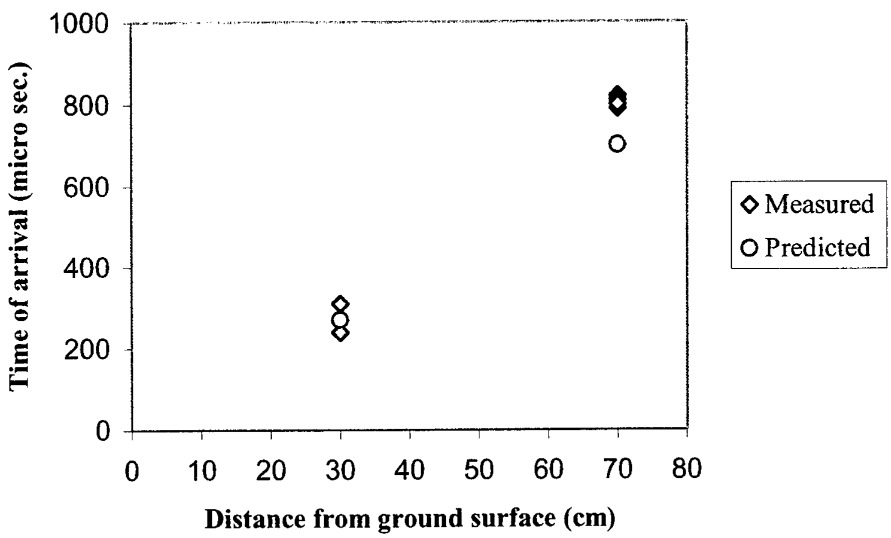


Figure 7: Time of arrival at transducers 1 and 2 positions, DOB =3cm.

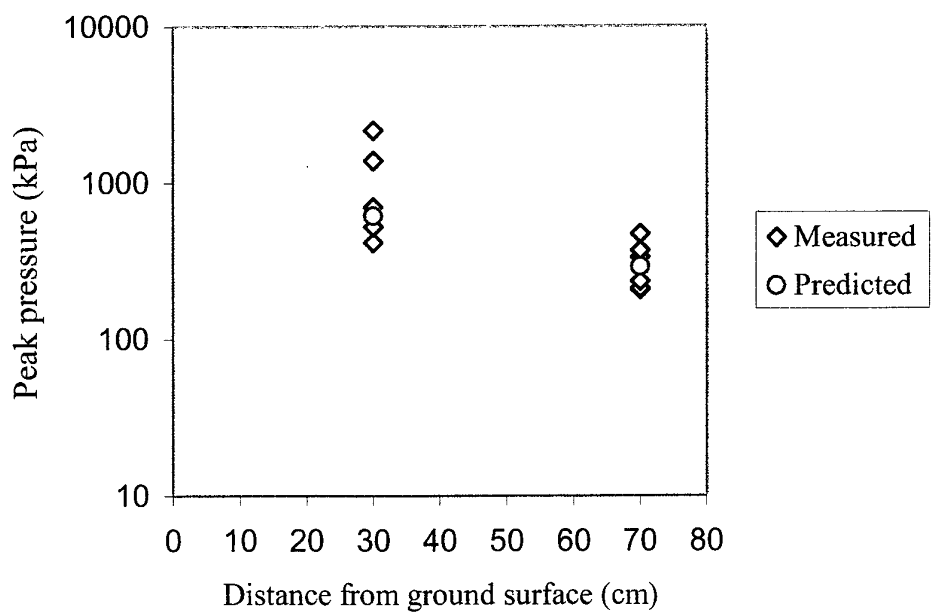


Figure 8: Peak pressure at transducers 1 and 2 positions, DOB =3cm

Figure 9 shows the comparison of the impulse at these positions. The predicted values are at the higher side of the range of the measured values. The discrepancies between the predicted and average measured values are 36% to 65% respectively.

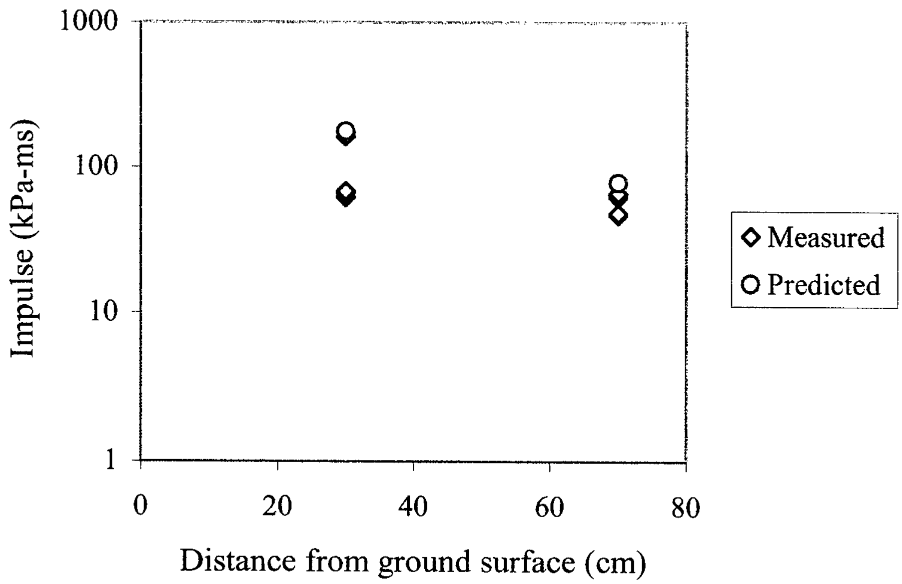


Figure 9: Impulse at transducers 1 and 2 positions, DOB =3cm.

The comparison of the time of arrival, peak overpressure and pressure impulse are summarised in Table 2.

Table 2: Measured and Predicted Values of Time of Arrival, Peak Overpressure and Positive Phase Impulse

DOB	Position above soil	Time of arrival (μs)			
		Measured			Predicted
		lowest	highest	average	
3 cm	30 cm	240	310	266.0	270
	70 cm	700	820	784	710
0	30 cm	90	102	94.8	90
	70 cm	254	317	285.6	300
		Peak overpressure (kPa)			
		Measured			Predicted
		lowest	highest	average	
3 cm	30 cm	414.1	2,157	724.8	613.3
	70 cm	207.4	468.5	304.5	290.1
0	30 cm	1,970	4,320	2,797	1,359
	70 cm	680.0	1,695	1,189	580.8
		Positive phase impulse (kPa-ms)			
		Measured			Predicted
		lowest	highest	average	
3 cm	30 cm	61.3	176	106.8	174.5
	70 cm	46.2	65.5	57.2	77.9
0	30 cm	70.6	97.5	85.8	86.0
	70 cm	97.2	126	116.4	137.5

Figure 10 plots the comparison of the displacement of the ejecta front. The trend of displacement vs time from the prediction agrees well with that from the measurement. The predicted values are about 10% to 15% higher than the measured results.

Figure 11 plots the comparison of the width of the soil crater. Good agreement between the prediction and the experiment is achieved. The predicted values are slightly lower than the measured ones.

Figures 12 and 13 show the comparisons of the height and width of the detonation products cloud respectively. The agreement between the prediction and experiment is good in both cases.

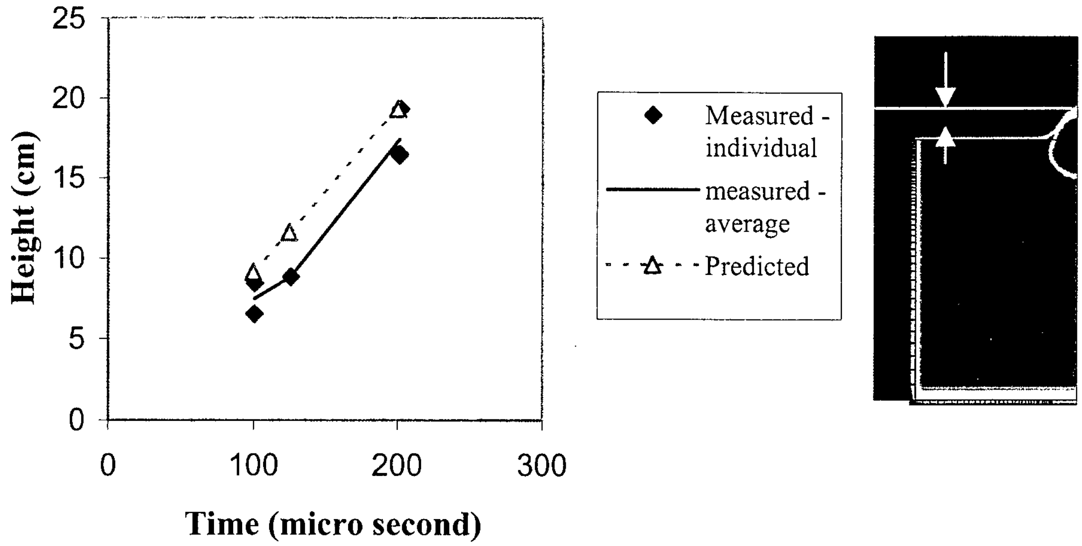


Figure 10: Displacement of ejecta front, DOB =3cm

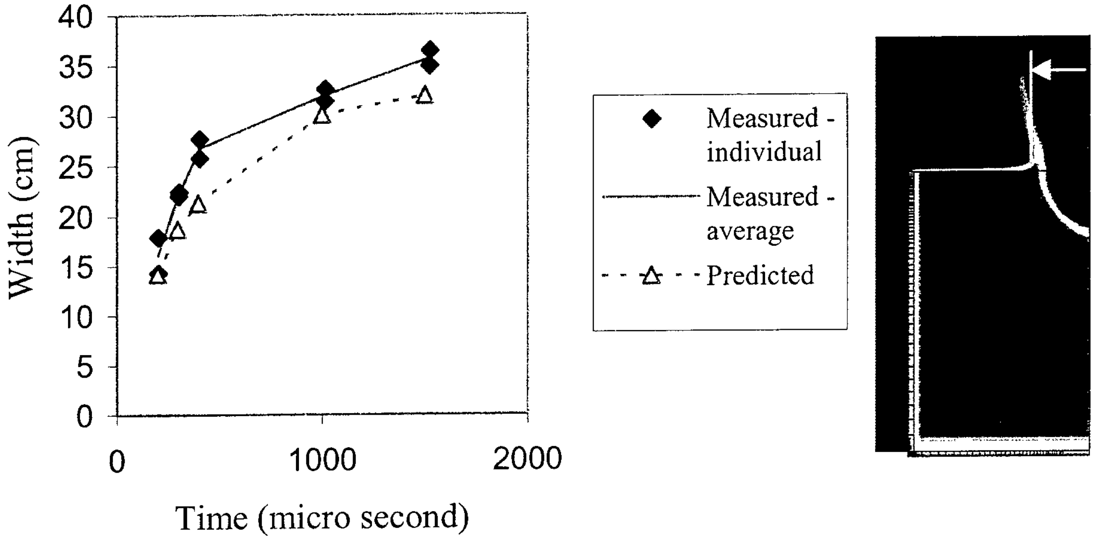


Figure 11: Width of crater, DOB =3cm

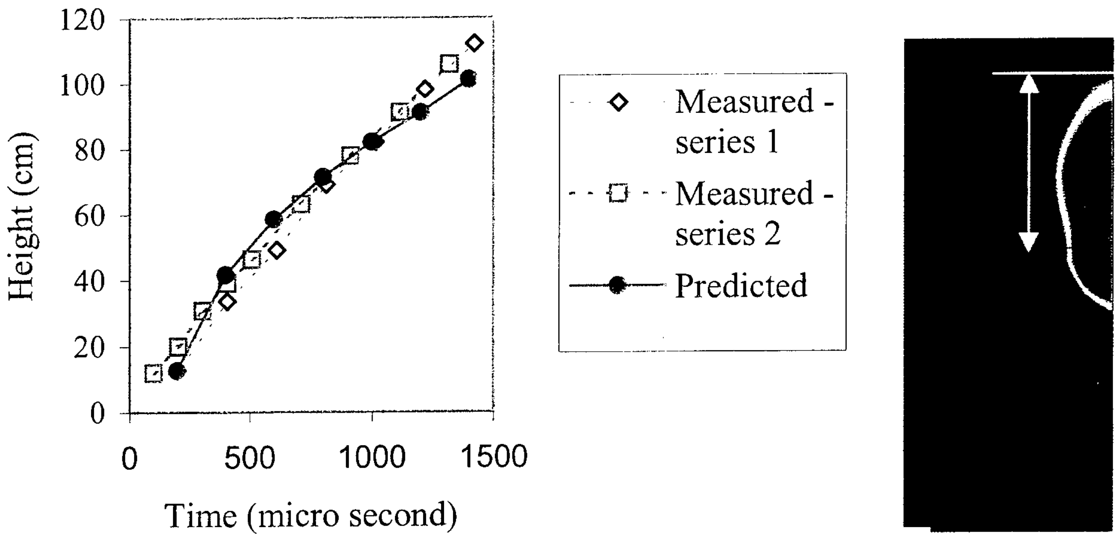


Figure 12: Height of detonation products cloud, DOB =3cm

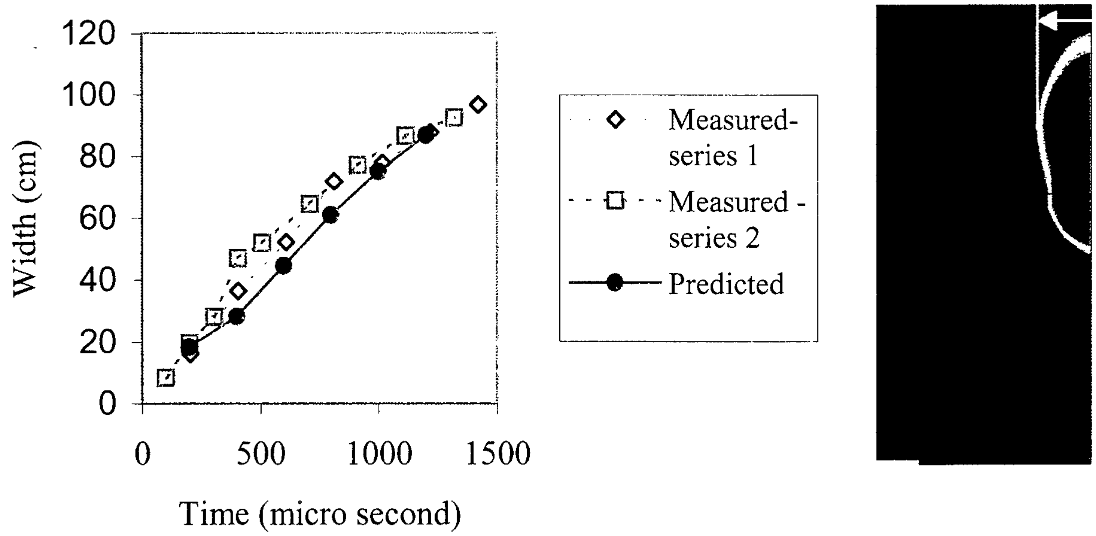


Figure 13: Width of detonation products cloud, DOB =3cm

3.3 Comparison with Experimental Results – DOB = 0

The same comparisons as above were made.

Figures 14, 15 and 16 and Table 2 show the comparisons of the time of arrival, peak overpressure and positive phase impulse. Similar comments as in the DOB = 3cm case above can be made except that the predicted overpressure is even lower than the measured.

The comparisons for the displacement of ejecta front, width of crater, and height and width of detonation products cloud are very similar to those in the case of DOB = 0 and thus the descriptions are omitted.

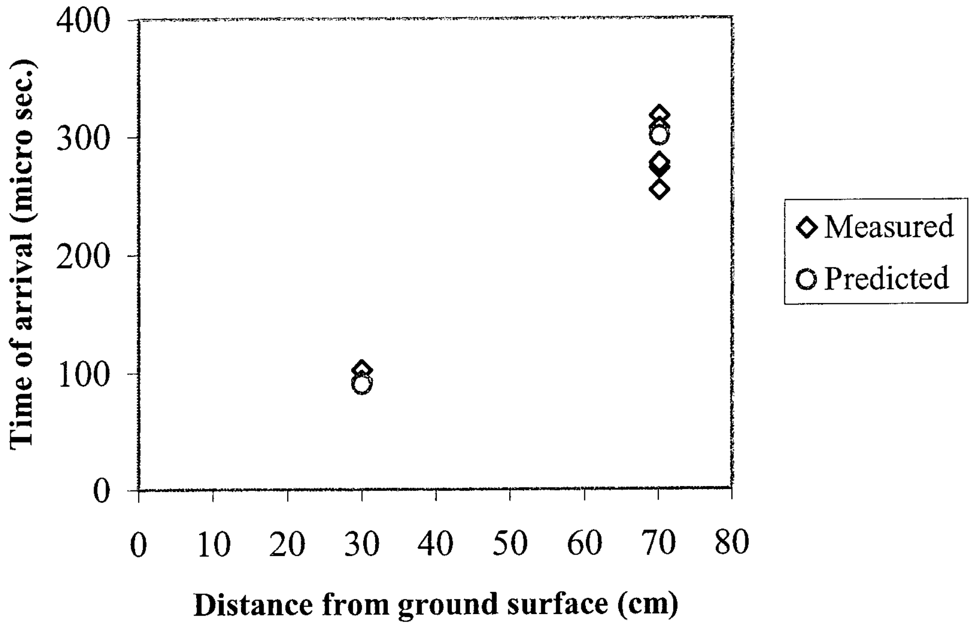


Figure 14: Time of arrival at transducers 1 and 2 positions, DOB =0

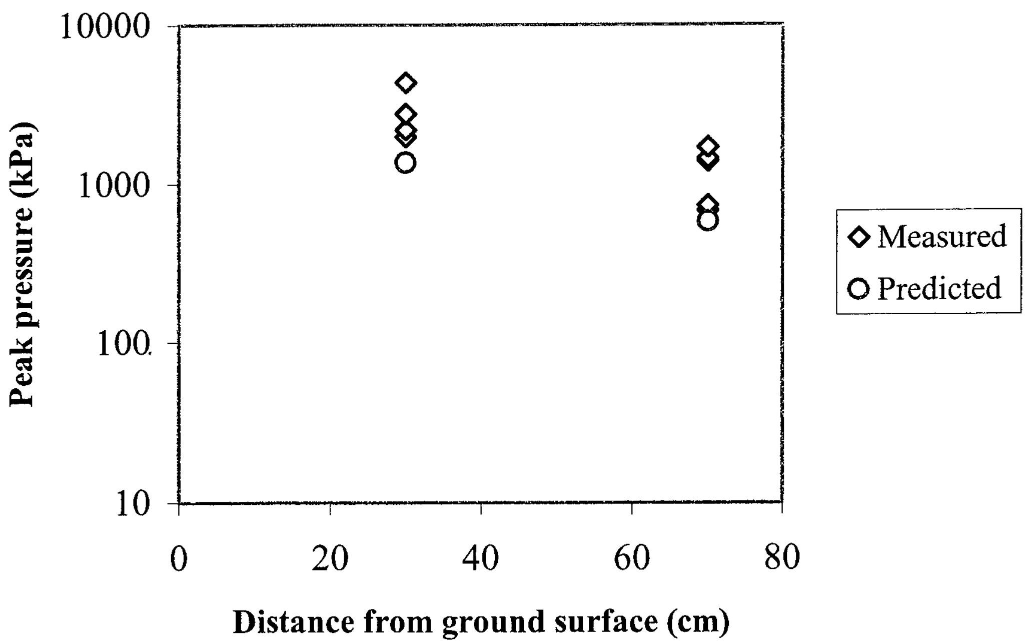


Figure 15: Peak pressure at transducers 1 and 2 positions, DOB = 0

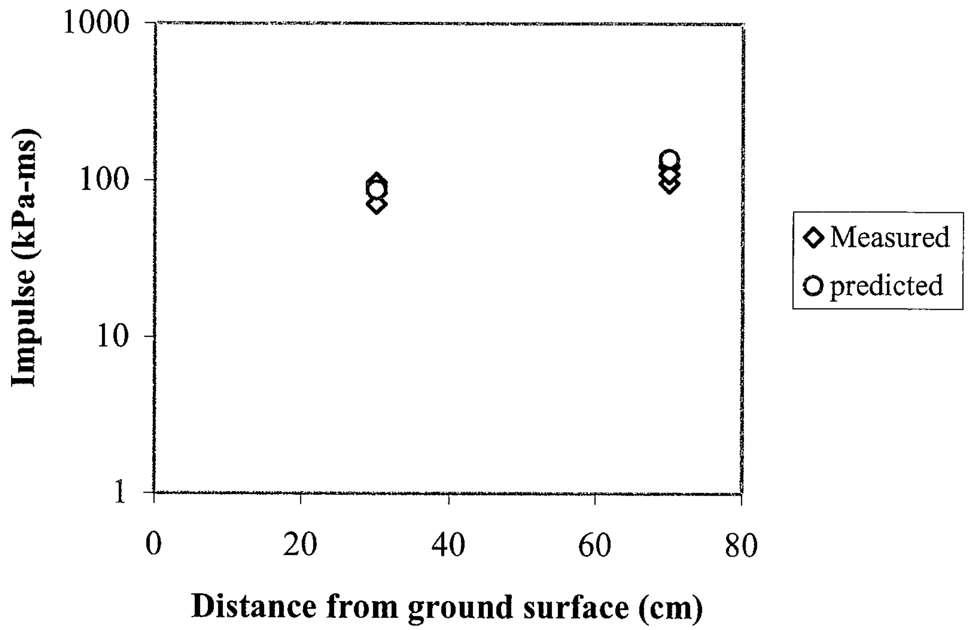


Figure 16: Impulse at transducers 1 and 2 positions, DOB =0cm.

3.4 Discussions about Overpressure and Impulse Predictions

Peak pressure and positive phase impulse are the most relevant loading factors for a structure response analysis. Thus if the impulse is the dominant factor in an application, then the Dyna results would indicate an overload of the structure compared with the measured results. On the other hand if the peak overpressure is the dominant factor, Dyna would noticeably underload the structure.

It is worth noting that it is reported in Reference [1] that two series of tests were conducted. In series 1 tests, the shape of the C4 charge was a little distorted and the mass of it was slightly more. In addition there was a little cavity observed above the detonator. The measured overpressure and positive phase impulse in series 1 tests were overall lower than those measured in series 2 tests (Table 3). In the analysis conducted above it was felt that the difference of these two series of tests did not warrant two separate models and thus the test results from them were not distinguished.

To improve the overpressure prediction, a fine mesh has to be used. Symmetry conditions should be used wherever possible to reduce the mesh size and allow a finer mesh to be used without increasing the total number of elements. To further improve the overpressure prediction, pressure scale-up (calibrated using experimental results) may need to be considered. Some optional ways are:

(1) The parameters in the EOS may be adjusted to match the experimental results. Besides the considerations from a numeric approximation point of view, a theoretical base for the scale-up is the consideration that in the relatively lower pressure range the available EOS of explosive materials may not be very accurate [5].
(2) If the peak overpressure is the dominant factor in an application a larger charge may be considered;

The proposed scale-up technique needs to be investigated before it can be applied.

Table 3: Measured and Predicted Values of Time of Arrival, Peak Overpressure and Positive Phase Impulse (Series 2 tests results only)

DOB	Position above soil	Time of arrival (μs)			
		Measured			Predicted
		lowest	highest	average	
3 cm	30 cm	270	310	290	270
	70 cm	700	790	757	710
0	30 cm	90	102	95	90
	70 cm	254	277	268	300
		Peak overpressure (kPa)			
		Measured			Predicted
		lowest	highest	average	
3 cm	30 cm	1,385	2,157	1,771	613.3
	70 cm	332	469.5	390	290.1
0	30 cm	1,970	4,320	3,006	1,359
	70 cm	1392	1,695	1,511	580.8
		Positive phase impulse (kPa-ms)			
		Measured			Predicted
		lowest	highest	average	
3 cm	30 cm	163	176	170	174.5
	70 cm	64.1	65.5	64.8	77.9
0	30 cm	70.6	97.5	83.7	86.0
	70 cm	111	126	121	137.5

4. Conclusions

(1) Compared with experimental results Dyna simulation for a landmine-explosion process is reasonably good. Predictions of geometry of initial fireball expansion, formation of soil ejecta and crater, and expansion of cloud of explosive product agree with experiment observations reasonably well.

(2) Dyna under predicts the overpressure. Compared with the average measured values, The prediction is lower by up to 50%. However the measured values are rather scattered. The predicted pressure is at the lower side of the range of the measured values. Dyna over predicts the impulse. Similarly the measured values are rather scattered. The predicted pressure is at around the upper side of the range of the measured values.

(3) Overpressure prediction is sensitive to the mesh density. To improve prediction accuracy, a fine mesh needs to be used. In addition pressure scale-up techniques (calibrated using experimental results) may be utilised. Further investigation about the effect of this scale-up needs to be carried out.

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This report describes the benchmark case applying LS-Dyna3d (Dyna) to simulate explosion in soil and air. Dyna simulation is compared with results from a well-defined landmine-explosion experiment. The agreement is reasonably good. This work has provided a base for further simulation of a system involving a structure, such as an army vehicle, subject to a landmine explosion.